Effects on Ferroelectric Thin-Film Stacks and Devices for Piezoelectric MEMS Applications at Varied Total Ionizing Dose (TID)

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Abstract: *Lead zirconate titanate (PZT) based thin films play a key role in a wide variety of applications due to its ferroelectric, piezoelectric, and pyroelectric properties. This work provides information on the effects of ^{60}Co radiation at different total ionization doses (TID) on the ferroelectric, dielectric, and piezoelectric properties of PZT PiezoMEMS actuator devices with two different top electrodes. Overall, the devices with IrO_2 top electrode were less impacted by the irradiation compared to the Pt top electrode devices.*

Keywords: lead zirconate titanate; PZT; actuator; radiation; gamma; total ionization dose; TID; top electrode; Pt; IrO2; polarization; PE; hysteresis; permittivity; strain; ferroelectric; dielectric; piezoelectric

Introduction

Ferroelectric thin films and devices are vital components for numerous applications such as non-volatile memory[1], sensors and actuators[2], RF devices[3], and energy harvesting systems[4]. The multifunctional properties of ferroelectric materials: dielectric, piezoelectric, pyroelectric, and electrostrictive material properties make these ideal for microelectromechanical system (MEMS) devices. Of specific interest are lead zirconate titanate (PZT) thin films, which have been used for filters[5], infrared radiation (IR) detectors[6], mechanical logic relays[3], digital computation elements for low power systems[2,3], and millimeter-scale robotics[2,3] applications. With the decreasing size in satellite technology[7,8] and the functionality of these devices, the Department of Defense can utilize these components for Satellite Communications, Intelligence Surveillance and Reconnaissance, Space Control, Space Environmental Monitoring, Satellite Operations, as well as safety monitoring and security applications in other radiation rich environments, such as nuclear reactors. Previous work has been focused on evaluating the radiation effects on ferroelectric properties for ferroelectric memory[9-12], however little research has been performed in understanding the effects of radiation on the electromechanical properties of materials and devices, therefore this is of the upmost importance for the advancement of this technology in extreme hazardous environments.

The large dielectric and piezoelectric response in PZT thin films, are largely due to the presence of hysteretically and non-linearly mobile internal interfaces, e.g. domain walls and eventual phase boundaries. Radiation exposure is expected to largely affect such defect-defect interactions (e.g. pinning/unpinning of domain walls on point defects, grain boundaries, etc.) through both displacement and ionization events. However, prior research has primarily concentrated only on the effects of irradiation as polarization degradation in ferroelectric memory devices, while a more complete and complex picture of interaction of radiation with the functional material stacks in MEMS device configuration has been missing. The goal of this work to address the mechanisms of radiation interaction with ferroelectric $Pb[Zr_{0.52}Ti_{0.48}]O_3$ thin films deposited on platinized silicon wafers, with IrO_2 or Pt top electrodes. All samples were irradiated with 0.2, 0.5, 1, 2, 5, and 10 Mrad (Si), using a ^{60}Co gamma radiation source at a dose rate of approximately 600 rad (Si)/sec at the Naval Research Laboratory (NRL). The ferroelectric, dielectric, and piezoelectric response of the material stack and actuator devices were characterized, as a function of top electrode stack material (IrO_2 or Pt).

Results

In Figure 1, a comparison of polarization hysteresis loops before and after exposure of the maximum dose of this study is shown. A 'pinching' characteristic at low voltages is observed in both irradiated samples, with the Pt electrode devices displaying a higher level of 'pinching' while the switching polarization rate appears to be more affected in the oxide electrode capped structure.

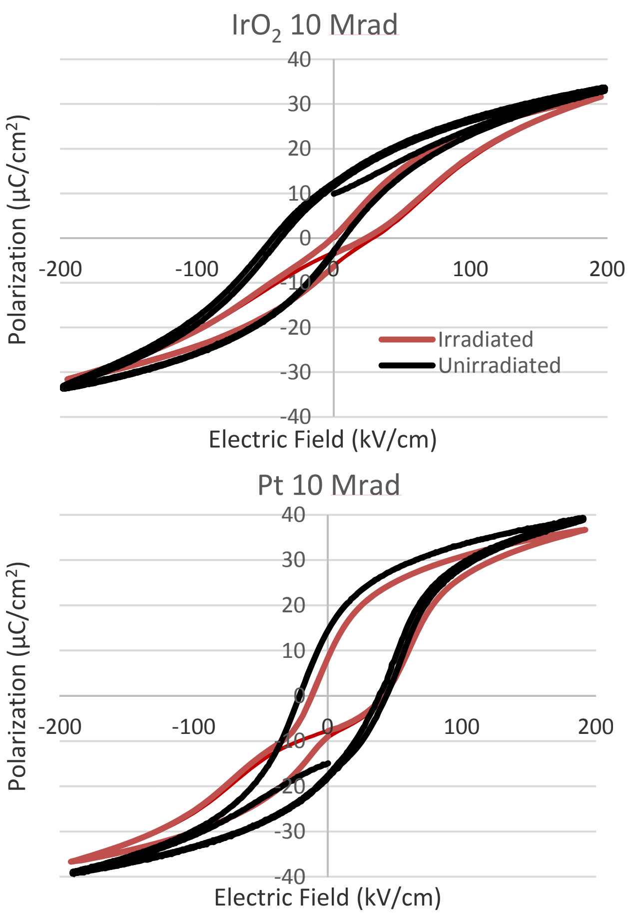

Figure 1. Comparison of P-E hysteresis loops before (black) and after (red) 10 Mrad ^{60}Co exposure of actuator devices with a IrO_2 (top) and Pt (bottom) top electrode.

In Figure 2, the maximum polarization (P_{max}) of the device is plotted vs radiation dose. Although the polarization values of IrO_2 capped devices are less than those of Pt, IrO_2 devices are less affected throughout the varying doses. Figure 3 shows a comparison of relative permittivity (ε) as a function of electric field before and after 10 Mrad ^{60}Co exposure of actuator devices with IrO_2 and Pt top electrode. The presence of a third peak corroborates the 'pinching' characteristic seen in Figure 1. Figure 4 shows the maximum relative permittivity trend as a function of dose. Since the PZT film performance varied between wafers, a percentage change from baseline was used to evaluate the radiation effects. Relative permittivity for IrO_2 electrode devices appear to be less affected throughout the different doses and the percent change follows a similar pattern. While Pt electrode devices have a smaller relative permittivity, the percent change show an improvement at low doses and significantly deteriorates at higher doses.

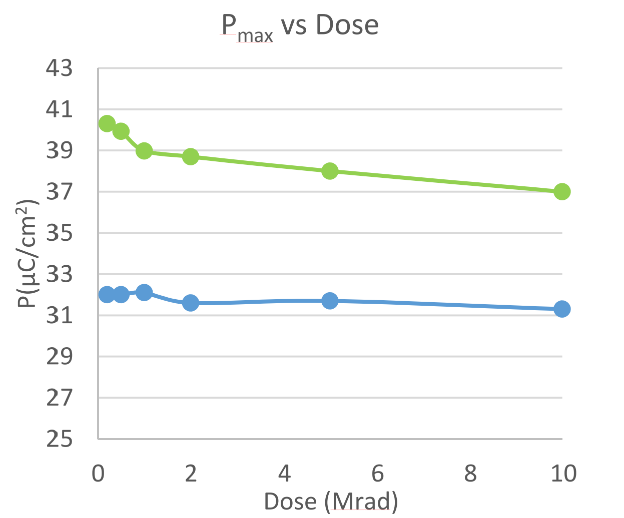

Figure 2. Trend of P_{max} vs radiation dose of actuator devices with a IrO_2 (blue) and Pt (green) top electrode shows less variation for IrO_2 samples.

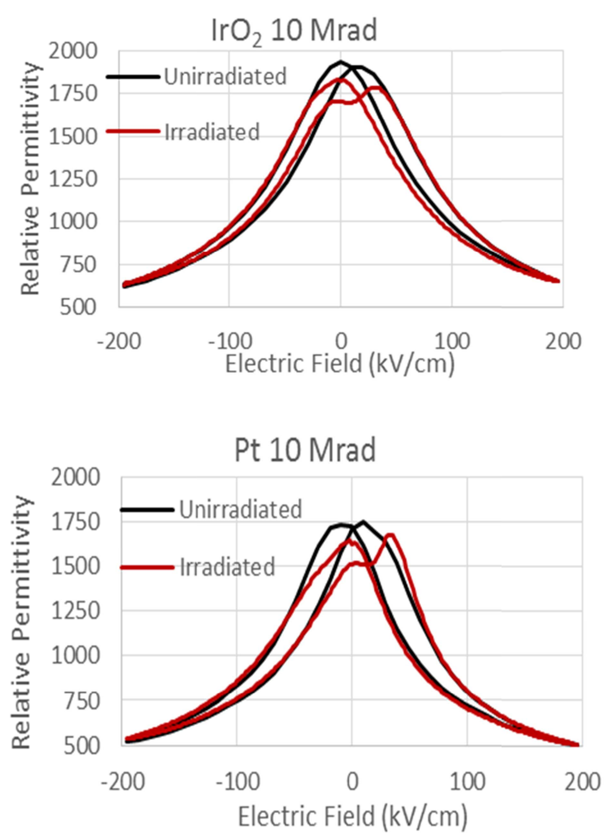

Figure 3. Comparison of relative permittivity as a function of electric field before (black) and after (red) 10 Mrad ^{60}Co exposure of actuator devices with IrO_2 and Pt top electrode respectively. Presence of third peaks suggest pinching.

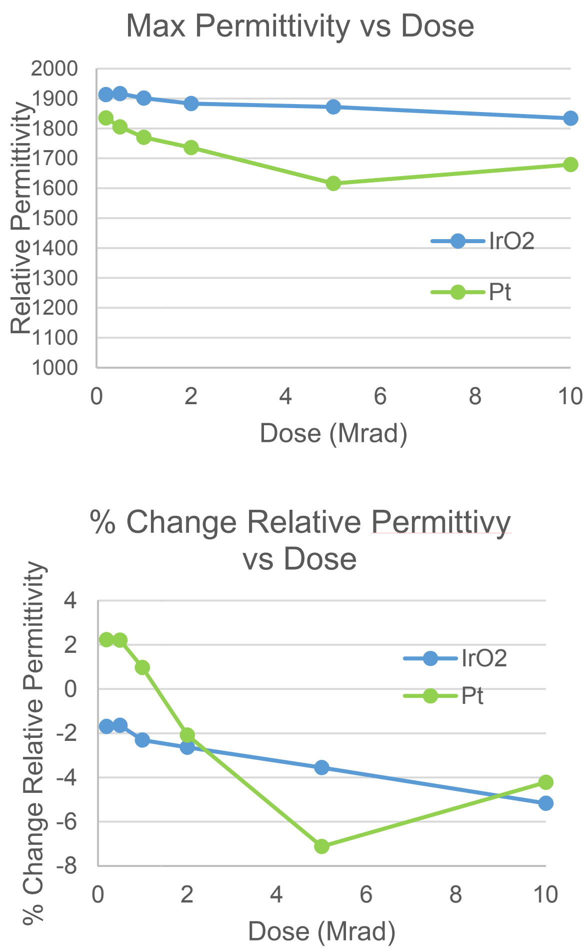

Figure 4. Trend of maximum permittivity values (top) and percent change of the relative permittivity (bottom) in reference to the baseline versus dose for devices with a IrO_2 (blue) and Pt (green) top electrode devices.

In addition to examining reversible and irreversible contributions to the dielectric response, the piezoelectric response of released cantilevers was tested for each of the dose levels in the study as seen in Figure 5. This data showed similar degradation in performance for both Pt-capped and IrO_2 capped cantilever structures, contrary to previous experiments. Interestingly, it appears that the majority of the degradation of the film performance appears below 500 krad (Si) and higher dose levels appear to have a more limited effect, especially in IrO_2-capped devices.

Conclusion

Overall, the oxide electrode capped structures and devices were less impacted by irradiation, than their metallic electrode counterparts. In examining the TID dose study, the irreversible contribution to the ferroelectric and piezoelectric effects appears to be contributing the majority of the change, while also showing large changes even at 100 krad (Si).

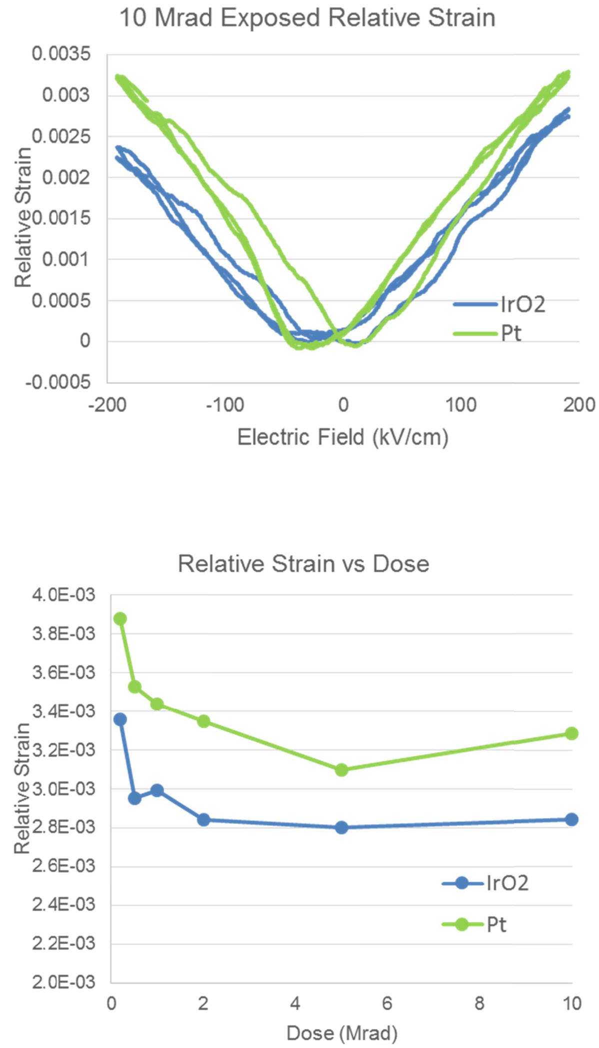

Figure 5. Comparison of actuator relative strain vs electric field after 10 Mrad Co^{60} exposure (top) and trend of relative strain vs radiation dose (bottom) of actuator devices with a IrO_2 (blue) and Pt (green) top electrode.

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